# Evaluate EMI reduction schemes with shielded-loop antennas

*Because of their small size and ability to respond only to the magnetic component of radiated fields, small shielded-loop antennas yield high resolution and accuracy as EMI/RFI probes.*

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Reducing RFI and magnetic interference from sources such as switching power supplies, high-frequency clocks and oscillators requires careful circuit layout and effective shielding. For evaluating the effectiveness of these schemes and for characterizing any magnetic field's magnitude and direction in general, small shielded-loop antennas serve as accurate directional measurement tools.

### Exclude E fields for higher accuracy

Unshielded antennas respond to both magnetic and electric fields. For applications where the interfering source is primarily magnetic in origin, as in switching power supplies (the application that this antenna probe was designed for), excluding electric fields produces more accurate measurements. When both magnetic and electric fields cause the interference, eliminating the electric field simplifies measurements. You can prevent antennas from responding to electric-field components with proper shielding.

Once you've eliminated the electric field, you can apply Faraday's Law to derive a loop's output resulting from the magnetic field. Derived from Faraday's Law for small loops such as that in **Fig 1,** the relative motion between a loop and a magnetic field induces a voltage at its terminals given by:

$$V_m = nB\omega A\cos\Theta \qquad (1)$$

where $V_m$ is the voltage induced at the loop's terminals, B equals magnetic flux density, n is the number of loop turns, $\omega$ is the field's angular frequency, A equals loop area and $\Theta$ represents the angle between the field and a vector of magnitude A perpendicular to the loop's plane. This equation, however, is valid only for small loops where circumference is less than a wavelength at the measured frequency.

To calculate this wavelength, use the equation

$$c = \lambda\nu$$

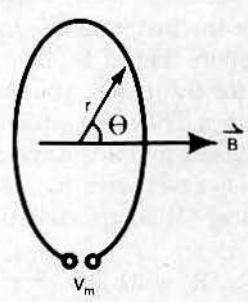


**Fig 1—Model an electrically small loop antenna** *as a stationary conductive loop in a changing magnetic field. Their relative motion induces a magnetic force at the loop's terminals.*

# Small loop antenna characterizes magnetic fields

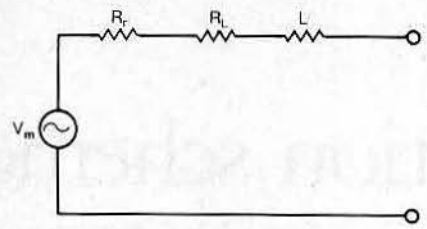


**Fig 2—The Thevenin equivalent circuit** *for an electrically small loop antenna shows such an antenna's low output impedance.*

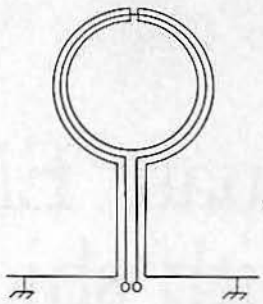

**Fig 3—The grounded shield** *surrounding the antenna loop blocks electric fields and passes magnetic fields.*

where c is the speed of light, $\lambda$ is the wavelength and $\nu$ is field frequency. As the loop's size approaches one wavelength, its response varies from point to point on the loop. Because **Eq 1** assumes an even loop response, it's invalid for large loops.

Resolution is another reason for using a small loop. Ideally, you want to be able to determine a field's characteristic at any point in space. However, because a loop is larger than a mathematical point, it covers several points in space and averages the individual field contributions. Smaller loops cover fewer points, average fewer individual contributions and provide better resolution.

Unfortunately, although small loop size aids resolution, loop sensitivity limits minimum loop size. As shown in **Eq 1,** loop response is proportional to area. When working with weak field strengths, you must either increase loop size or add turns.

### Matching probe to test equipment

When combining a loop probe with test equipment, you must also pay attention to impedance matching. Ideally, you want the loop's output impedance to be much less than the instrument's input impedance. If it is, you can ignore both. To help determine a loop's impedance at its terminals, you can model electrically small loops with a Thevenin equivalent circuit **(Fig 2).** In the model, you'll find a voltage source in series with a small radiation resistance $R_r$, loss resistance $R_L$ and small inductance. Calculate radiation resistance with

$$R_r \simeq 31{,}200 \left[\frac{Af^2}{C^2}\right]^2$$

where A is loop area, f equals magnetic field frequency and c is the speed of light. For loop inductance, use

$$L \simeq r\mu_o \left[L_n\left(\frac{16r}{d}\right) - 1.75\right]$$

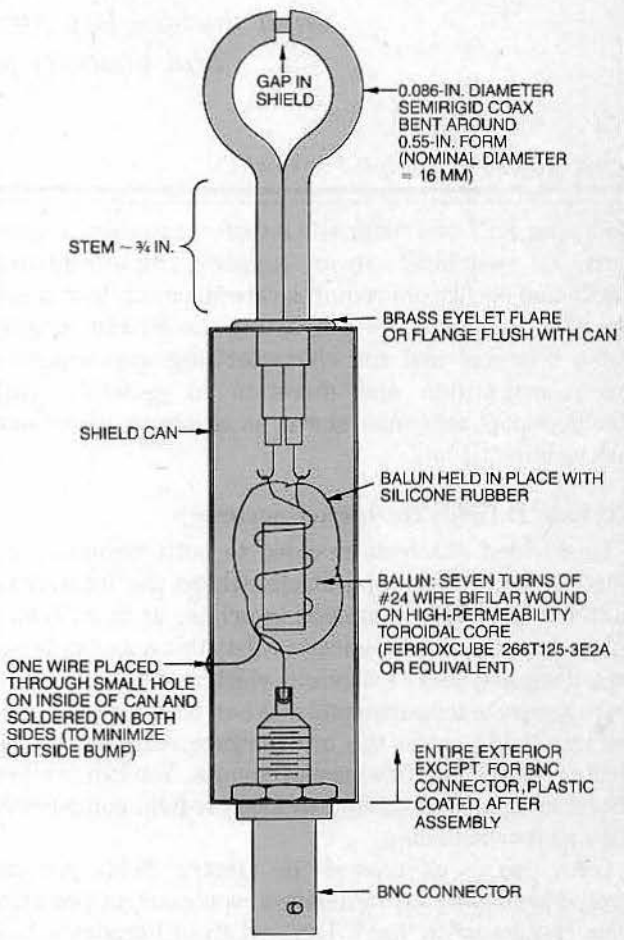
GAP IN SHIELD
0.086-IN. DIAMETER SEMIRIGID COAX BENT AROUND 0.55-IN. FORM (NOMINAL DIAMETER = 16 MM)
STEM ~¾ IN.
BRASS EYELET FLARE OR FLANGE FLUSH WITH CAN
SHIELD CAN
BALUN HELD IN PLACE WITH SILICONE RUBBER
BALUN: SEVEN TURNS OF #24 WIRE BIFILAR WOUND ON HIGH-PERMEABILITY TOROIDAL CORE (FERROXCUBE 266T125-3E2A OR EQUIVALENT)
ONE WIRE PLACED THROUGH SMALL HOLE ON INSIDE OF CAN AND SOLDERED ON BOTH SIDES (TO MINIMIZE OUTSIDE BUMP)
ENTIRE EXTERIOR EXCEPT FOR BNC CONNECTOR, PLASTIC COATED AFTER ASSEMBLY
BNC CONNECTOR

**Fig 4—Build a practical probe** *with a balun to maintain the loop's balance when connected to an unbalanced measuring device's input.*

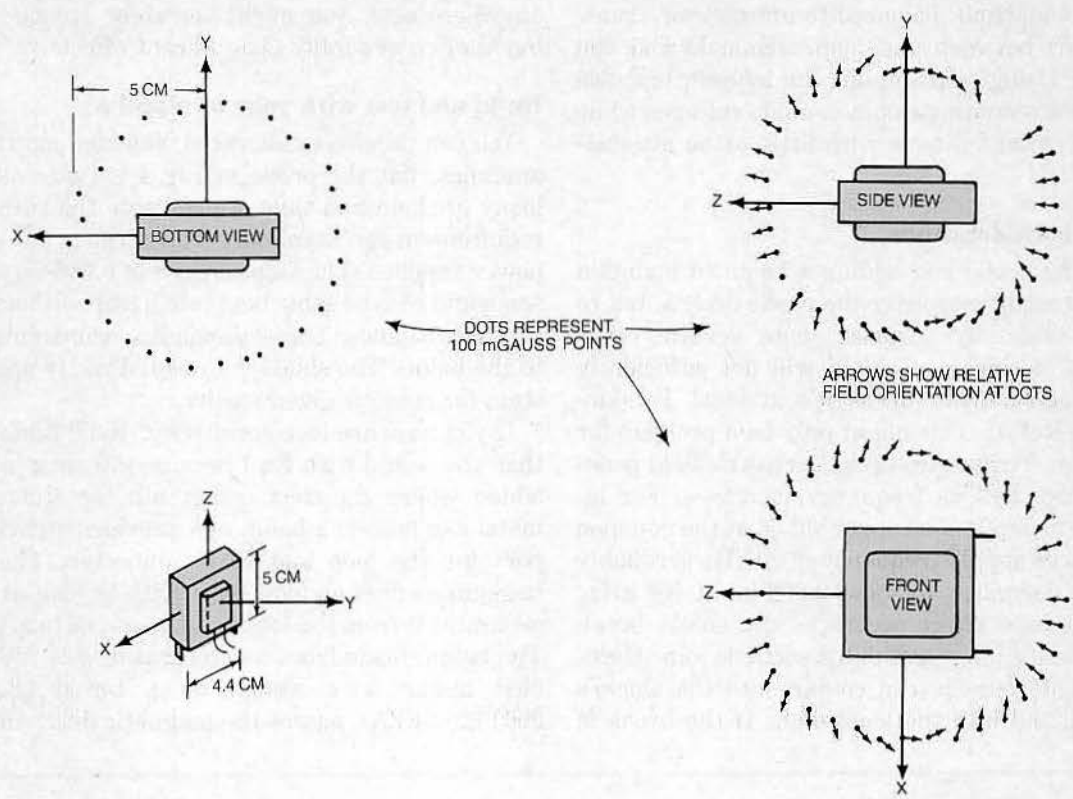


**Fig 5—You can plot the magnetic field** *generated by an E-core, switch-mode power-supply transformer by obtaining data with a magnetic field probe.*

where d is loop diamater, $\mu_0$ is a constant equal to $4\times\pi\times10^{-7}$ henrys/meter, and d is the wire's diameter.

The total Thevenin equivalent impedance for an electrically small loop is typically very small over a wide frequency band. For example, a 16-mm-diameter loop with 0.51-mm-diameter wire has a $1.56\times10^{-13}\Omega$ radiation resistance at 1 MHz and a 0.038-μH inductance. If, as in most cases, the antenna drives an impedance that's much greater, the voltage delivered to the instrument will equal $V_m$.

### Reducing electric field response

As mentioned before, eliminating antenna response to electric fields improves measurement accuracy and repeatability. The simplest way to reduce this response is to decrease loop size. Loop sensitivity to electric fields decreases as the square of loop size, while sensitivity to magnetic fields decreases directly with decreasing loop size (**Ref 1**). Ultimately, however, a severely reduced loop won't respond to even the magnetic field.

A more effective approach to reducing the electric field response uses a selective shield to attenuate only electric fields (**Fig 3**). However, you must break the shield at one point around the loop to prevent magnetically induced shield current (**Ref 2**) because current in the shield would prevent the magnetic field from reaching the loop probe.

### Match probes to instruments

You can also attenuate electric field response by paying attention to balancing. The basic loop antenna is inherently balanced; the potential difference produced by a uniform magnetic field across its output terminals is balanced with respect to ground. But if you connect a loop antenna directly to an unbalanced coaxial cable, an impinging electric field induces a signal in the shield that couples into the loop as a common-mode potential difference between the loop and ground. This common-mode signal can add to or subtract from the differential-mode signal produced by the magnetic field.

To test for this effect, rotate the loop's plane 180°. The loop encloses the same amount of magnetic flux in both positions, so it should respond with equal output voltages. If a significant portion of the response is due to the electric field, however, these voltages will be unequal because rotating the loop inverts the phase of the differential-mode (magnetic) signal but not the

phase of the common-mode (electric) signal.

One way to correct loop-to-instrument imbalance is to insert a wideband balanced-to-unbalanced transformer (balun) between the loop terminals and the coaxial cable. Doing so maintains the inherent balance of the loop by attenuating common-mode voltages while passing differential voltages with little or no attenuation (**Ref 2**).

### More subtle considerations

Shielding the probe and adding a balun to maintain its balance virtually completes the probe design, but to avoid being taken by surprise, note several other effects. First, a thin loop shield will not sufficiently reduce an electric field unless it's at least 10 skin-depths thick (**Ref 3**). This might only be a problem for you at very low frequencies because electric field penetration becomes less as frequency increases. For instance, the skin depth of a copper shield at the common switching power-supply frequency of 20 kHz is roughly 0.018 in., but decreases to about 0.008 in. at 100 kHz.

Another strange effect occurs at the shield break where the shield's inner and outer sections join. Here, current from its outside can couple onto the shield's inside surface and into the loop itself. If the break is made symmetrically (directly opposite the feed point), these shield currents cancel out. If the break is made anywhere else, you might see some strange outputs, but they're generally insignificant effects.

### Build and test with your own probe

You can purchase calibrated, shielded multiturn loop antennas, but the probe in **Fig 4** is twice as small as many of them and thus offers twice the resolution—a requirement for examining transformers for switching power supplies. The loop consists of 0.086-in.-diameter, semirigid coaxial cable bent into a loop with a stem that acts as a balanced transmission line connecting the loop to the balun. The shield is broken directly opposite the stem for reasons given earlier.

If you measure loop sensitivity, you'll find it greater than you would with **Eq 1** because effective loop area is added where the coax bends into the stem. A small metal can houses a balun and provides structural support for the loop and BNC connector. The can has negligible effect on loop sensitivity as long as the stem separates it from the loop by at least one loop diameter. The balun, made from seven turns of #24 AWG, enameled bifilar wire wound on a toroid (Ferroxcube 266T125-3E2A), passes the magnetic field's differential

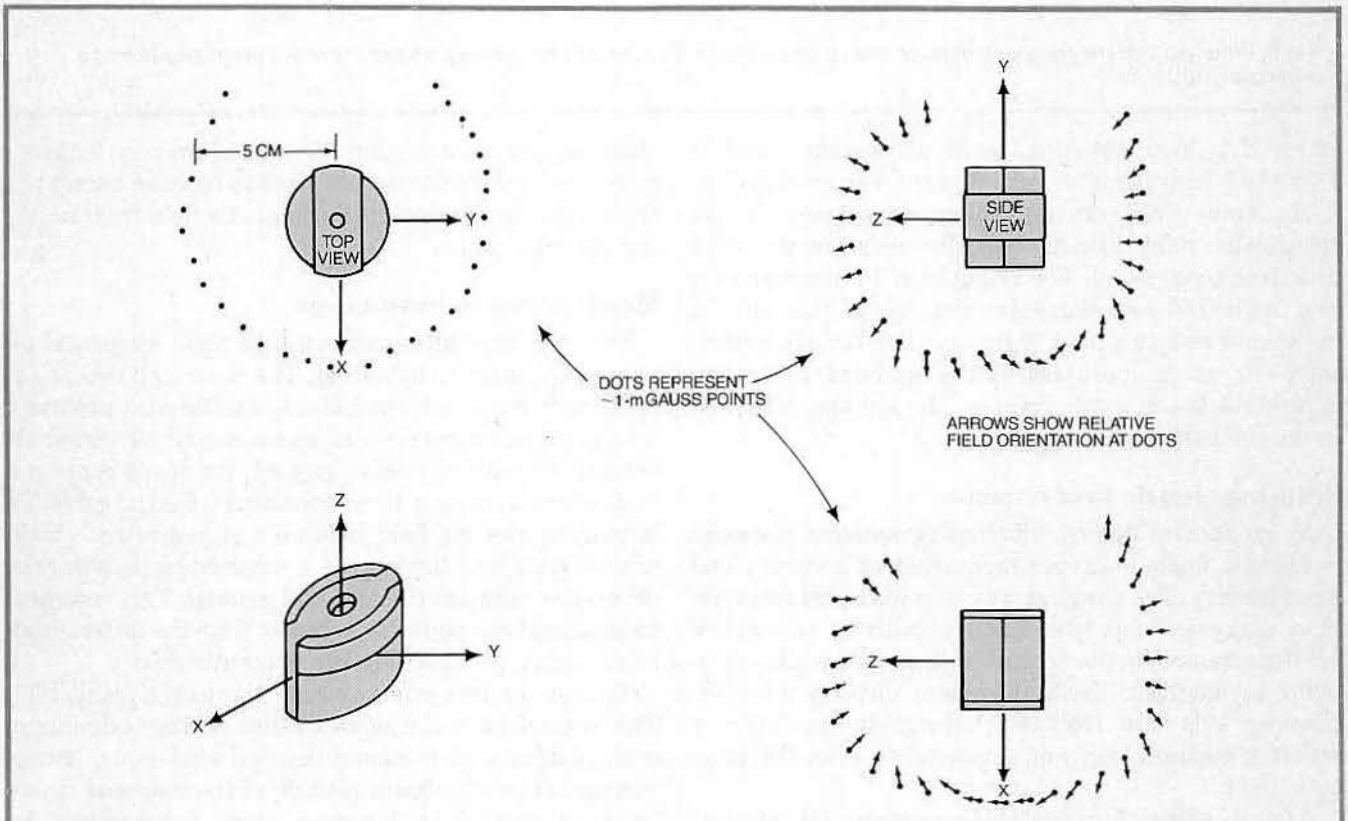


**Fig 6—The flux map for a cylindrical, switched-mode power-supply transformer** *differs from that of an E-core transformer. Take such differences into consideration when choosing a transformer for your application.*

## For more information...

The probe described in the article is not commercially available. The author designed and built it to his custom requirements. The companies listed below manufacture similar probes that might suit your application. For more information, circle the appropriate numbers on the Information Retrieval Service card or contact the manufacturers directly.

**Electro-Metrics Co**
100 Church St
Amsterdam, NY 12010
(518) 843-2600
**Circle No 703**
*Models MFA-25, MFG-25 and MFC-25 cost roughly $300*

**Perfection Mica Co**
(Magnetic Shield Co)
740 N Thomas Dr
Bensenville, IL 60106
(312) 766-7800
**Circle No 705**
*Model EP-102 costs roughly $80*

**Eagle Magnetic Co**
Box 24283
Indianapolis, IN 46224
(317) 297-1030
**Circle No 704**
*Model DL-100 flux probe costs approximately $150*

signal. To prevent shorting to live circuit points, use a rubber or plastic overcoat.

**Figs 5** and **6** show how to use a small loop antenna to evaluate transformer designs for a switching power supply. The probe characterizes the magnetic field in the immediate vicinity of each transformer. Connected to a spectrum analyzer (HP-8568A) through an external preamplifier, the probe's output voltage is displayed on the analyzer's CRT, and you can convert that value to flux density in milligauss.

**Fig 5** shows a rectangular E-core transformer in a 3-dimensional coordinate system. You can make a map of its magnetic field by placing the transformer at the center of a sheet of polar plotting paper (one sheet for each primary plane) and marking 100-mG flux-density contours. Because the small loop antenna responds only to field lines perpendicular to the loop plane, you can also determine the relative directions of the field lines, indicated in **Figs 5** and **6** with small arrows at each measurement point.

**Fig 6** illustrates flux maps for an alternate to the E-core design, a cylindrical pot-core transformer that operates with the same current. This time, rather than plotting 100-mG points, plot 1-mG contours and compare the two devices. You see that the pot-core's leakage fields are less than those of the E-core unit by approximately 40 dB.

### Measure shielding leakage, too

In other applications, you can use the loop to investigate shielding phenomena. For example, conductivity across the seams that join metal in a shield usually limits its effectiveness. Holes and seams perturb surface current flow in the shield and radiate magnetic fields. Using a shielded loop probe, you can investigate seam integrity by locating seams with excessive magnetic-field leakage. Similarly, you can evaluate a gasket material's shielding effectiveness and how mounting characteristics, such as gasket pressure and screw separation, affect shielding performance.

As an example of using the loop in **Fig 4** for measuring shielding performance, consider evaluating the effectiveness of a desktop computer's metal-coated top cover. Hold the loop directly over the cover near its seam so it doesn't move relative to internal circuitry when you remove the top cover. Then connect the probe to a spectrum analyzer (such as an HP-8568A using an HP-8447D preamplifier).

Now measure magnetic-field emissions at frequencies to 100 MHz with the cover on and off. By reading the spectrum analyzer you can identify most emission sources as being harmonics of internally generated signals. In this case, the cover reduced discrete magnetic emissions by 9.5 dB at 62.4 MHz and 13.4 dB at 49.9 MHz, or roughly 10 dB overall. **EDN**

## References


1. Whiteside, H, and King, R W, "The loop antenna as a probe," IEEE Transactions on Antennas and Propagation, May 1964, pgs 291-297.
2. Ott, H W, *Noise Reduction Techniques in Electronic Systems*, John Wiley & Sons, NY, 1976, pgs 47-48, 71-76.
3. Libby, L L, "Special aspects of balanced shielded loops," proceedings of the IRE, Vol 34, September 1946, pgs, 641-646.
4. Stutzman, W L and Thiele, G A, *Antenna Theory and Design*, John Wiley & Sons, NY, 1981, pgs 102-103.


## Author's biography

**Scott Roleson** is an electromagnetic-compatibility engineer at Hewlett-Packard Co (San Diego, CA). He is an advisor in EMC matters involving testing and new products. A member of the IEEE, the Antennas and Propagating Society and the Electromagnetic Compatibility Society, Scott holds a BSEE from Arizona State University and an MSEE from the University of Arizona. His hobbies include hiking, ham radio and computers.

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